HIGH PRESSURE ACCELERATION OF AN ARC-DRIVEN METAL SLUG IN A RAILGUN

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Summary

The successful acceleration in a railgun of an intact, arc-driven metal slug subjected to a peak pressure of ~ 0.7 GPa is described. The techniques and principles of accelerating metal slugs at very high pressures are reviewed. High pressure operation is required for applications requiring maximum velocity in guns of limited length. The development of metal projectiles is useful because of the availability of a wide range of properties such as strength, density, ductility, hardness and melting point. For example, high tensile strength and ductility make metal projectiles resistant to damage resulting from high-pressure demuzzling in comparison to ceramic projectiles which are characterized by enormous compressive strength, but low tensile strength and ductility. The electrical conductivity of metals necessitates the protection of metal projectiles from erosion by the armature current during acceleration. The problem of designing protective sabots of minimum mass and capable of operating at very high pressure is discussed.

Introduction

This paper considers the high-pressure acceleration in railguns of arc-driven metal slugs. The successful firing of a titanium slug accelerated from rest by a pressure of ~ 0.7 GPa is described. With proper projectile design, gun design, and firing technique, metal slugs can very likely be successfully fired at much higher pressure. Metals with tensile strengths in excess of 3 GPa are available and under the proper conditions, a projectile can be overstressed while it is confined in the bore.

In the present experiment, the railgun survived the firing without serious structural damage, and the gun has been fired again after refinishing of the bore to remove arc damage. At higher pressures, however, railguns will be damaged beyond repair after a single shot. The problem of designing railguns for operation at very high pressure is therefore one of designing guns that are inexpensive enough to discard after a single shot. Alternatively, the guns could be designed to have rapidly reloadable expendable components.

In principle, arbitrarily high muzzle velocities can be achieved in a low pressure gun if the gun is long enough. But for many applications, practical considerations (cost, mobility and aiming, for example) limit the length of the gun. In a gun of limited length, muzzle velocity can be increased by operating at higher pressure.

If a 15-mm long aluminum slug were accelerated by a constant base pressure (no friction) of 0.5 GPa, a muzzle velocity of 5 km/s would be achieved in a one-meter gun. If the same projectile could be accelerated without friction by a constant pressure of 5 GPa (a challenging task), a velocity of 16 km/s could be achieved. The muzzle velocity achieved with short, powder-driven guns firing metal projectiles is one or two kilometers per second.

Projectile Design

The acceleration in railguns of metal slugs is an enticing prospect. Metals have ductility, high tensile and compressive strength, and are available in densities ranging from 500 to 2,000 kg/m^3. By comparison, ceramic materials, which are attractive because of their high compressive strength and low electrical conductivity, are brittle, have low tensile strength, and low ductility. The high tensile strength and ductility of metal projectiles makes them resistant to demuzzling damage resulting from the sudden release of compressive strains as the projectile exits the gun. With low strength projectiles (polycarbonate) or brittle, low tensile strength ceramic projectiles, we would expect the projectiles to shatter upon exiting unless the accelerating pressure is reduced nearly to zero while the projectile is still confined in the bore of the gun.

The most obvious disadvantage of metal projectiles is that the metal slug must be protected from becoming involved with the armature current. If the armature current flows in the metal slug, the projectile will be eroded, as shown in Figure 1, or even destroyed.

One method of protecting metal slugs from the driving arc which has been successfully tested by the authors is illustrated in Figure 2. The polycarbonate disk is a gas seal; the corundum disk seals the back of the projectile to protect the titanium slug from the armature. The titanium slug is protected by a circumferentially wound fiberglass-epoxy sleeve. Note the circumferential grooves cut in the slug to prevent the fiberglass sleeve from sliding off the slug during firing.

It is desirable to minimize the thickness of the protective fiberglass sleeve for two reasons. We wish to maximize the fraction of the total mass devoted to the payload (the metal slug). Secondly, if the sleeve is too thick, excessive shear is developed between the projectile and the sleeve during acceleration. This effect is illustrated with a simple calculation.

A cylindrical slug of density ρ_1, radius r_1, and length L is encased in a protective sleeve of density ρ_2, outside radius r_2 and length L. The assembly is accelerated without friction by a base pressure P. The protective sleeve is less dense than the slug and tends to accelerate at a higher rate. The tendency of the sleeve to outrace the slug is resisted by a shear force borne in the cylindrical seam between the sleeve and the slug. The average shear stress τ in this seam is:

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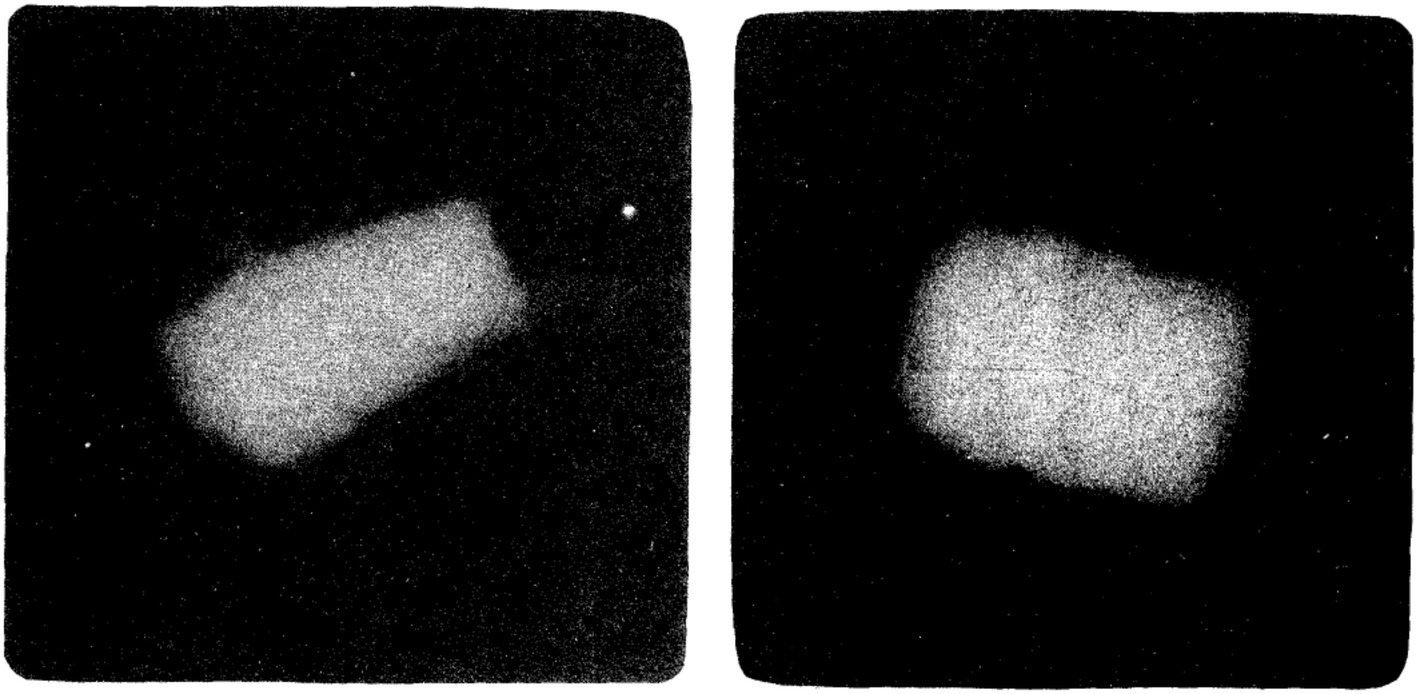

Figure 1. Flash radiographs of in-flight titanium projectiles

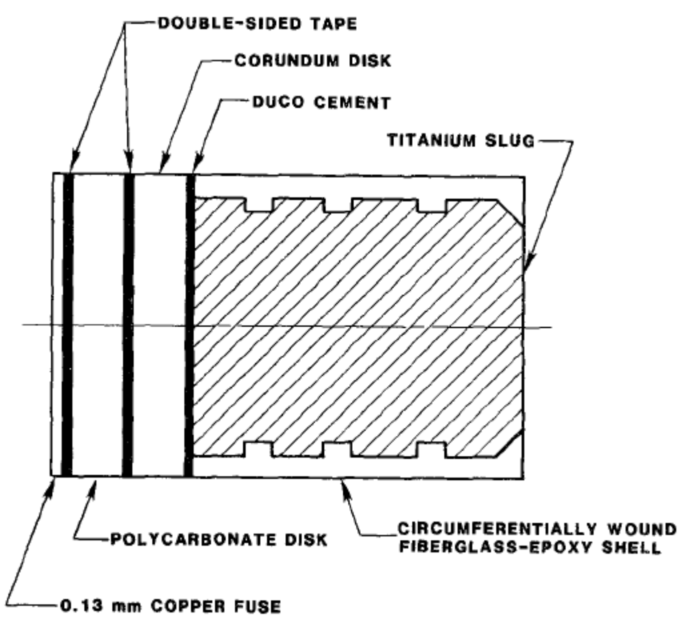

Figure 2. Projectile design

$$\tau = \frac{Pr_1(r_2^2 - r_1^2)(\rho_1 - \rho_2)}{2L[\rho_2(r_2^2 - r_1^2) + \rho_1 r_1^2]} \quad . \qquad (1)$$

Consider the average shear stress in the seam between a 15-mm outside diameter, 15-mm long fiberglass-epoxy sleeve (density 180 kg/m^3) and a titanium slug (450 kg/m^3) accelerated by a pressure of 1 GPa. A reasonable maximum shear stress is 3 or 4 MPa. If the thickness of the sleeve is less than one millimeter, the shear stress is acceptable.

Projectile design involves both art and science. Figure 1 shows that the left projectile has been erroded by the armature current. The right projectile is intact. Close inspection of the radiograph reveals that the circumferential grooves and the bevel on the end of the slug are still visible. The corundum disk was attached to the titanium slug with double-sided tape in the projectile on the left, with Duco cement on the right. Apparently the double-sided tape formed an inadequate seal to protect the titanium, the Duco cement formed an adequate seal.

Firing Technique

A projectile accelerating from rest in a railgun is vulnerable. As the railgun flexes in response to the magnetic pressure on the rails, the bore may change shape, clamping the projectile. Or, as the rails are driven apart behind the projectile, they may scissor together in front of the projectile. (These problems are peculiar to heavy projectiles fired at high pressure.) As the projectile moves down the bore gaining speed, it may even overtake previously launched disturbances propogating down the gun. However, once it gains sufficient speed, the projectile becomes indifferent to disturbances in the railgun structure which originate behind the projectile. The projectile travels in an undisturbed bore, outracing all disturbances.

The speed of sound in copper is 3.6 km/s. Longitudinal displacements (compression waves) travel at that speed. More troublesome lateral displacements (shear waves) travel at half that speed. We would expect that the speed at which the projectile becomes safe from bore-projectile interferences lies in the range between 2 and 4 km/s. A 15-mm long aluminum projectile accelerated by a pressure of 1 GPa achieves a velocity of 2 km/s in a distance of 80 mm, a tungsten projectile in 600 mm.

Thus, there are different strategies for the low velocity section and the high velocity section of the railgun. In the low velocity section, the maximum allowable operating pressure is determined by the

stiffness of the gun. The operating pressure must be low enough to avoid interferences. When the projectile enters the high velocity section of the gun, the pressure may be increased. To the fast-moving projectile, the railgun bore acts as an extremely rigid confining cylinder. In theory, this rigid confinement enables a properly designed projectile to withstand pressures far in excess of the strength of the metal slug. It is not obvious which effect limits the maximum allowable operating pressure in the high velocity section of the gun. If the operating pressure exceeds the strength of the metal slug by too great a margin, excessive friction may develop resulting from the plastic expansion of the projectile against the railgun bore. Other possible limitations on operating pressure are mechanical failure of the protective sabot, excessive electrical losses and the effects of radiation from the armature.[1]

A highly stressed projectile may explode when it exits the gun. To launch an intact projectile, it is necessary to reduce the operating pressure as the projectile approaches the muzzle. This may be done by crowbarring the rails of the gun.

As the projectile rings in response to the sudden release of pressure as it demuzzles, we would expect a highly-compressed projectile to experience tensile stresses similar to the compressive stresses present just before demuzzling. A good rule of thumb is to reduce the railgun operating pressure to the tensile strength of the metal slug as the projectile approaches the muzzle.

Railgun Design

This section discusses briefly and qualitatively the design of a one-shot railgun (or a railgun with rapidly reloadable expendable components) to operate at very high pressure to produce high muzzle velocity in a limited length.

The necessity for the low velocity section of the gun to operate successfully at very high pressure results in a compromise of the magnetic design. Stringent stiffness requirements necessary to avoid destructive interferences between the slow-moving projectile and the gun yield a railgun design with a low inductance per unit length.

However, in the high velocity section of the gun we are free to pursue an aggressive magnetic design. This design freedom results from two considerations. In the high velocity section of the railgun, structural stiffness is an incidental concern. The fast-moving projectile is safe from interferences. Secondly, because of the one-shot design, survivability of the gun is not a constraint. Severe arc damage to the bore and overheating and plastic deformation of the rails can all be tolerated. The rails need not be constrained against rebound as the gun relaxes after firing. The high velocity section of the railgun can be designed with a high inductance per unit length. Indeed, the inductance per unit length can increase from the beginning to the end of the high velocity section because the duration of the current flow at any point in the gun declines from the muzzle to the breech.

We have discussed the necessity for the operating pressure to decline as the projectile approaches the muzzle to prevent demuzzling and subsequent destruction of an overstressed projectile, and that this pressure reduction can be effected by diverting the armature current into a crowbar. This reduction of pressure may be assisted by spoiling the magnetic performance of a short section of railgun at the muzzle, that is, by adding a short section of railgun at the muzzle with a drastically reduced inductance per unit length.

In summary, a short one-shot railgun for accelerating metal projectiles at very high pressure consists of three sections. The low velocity section has high stiffness and low inductance per unit length, the high velocity section has low stiffness and high inductance per unit length, and the demuzzling section has drastically reduced inductance per unit length. If a square current pulse were delivered to such a gun, the operating pressure would jump as the projectile entered the high velocity section, increase gradually as the projectile proceeded through the high velocity section, and decline suddenly as the projectile entered the demuzzling section. The operating pressure could be further tailored by increasing the current as the projectile entered the high velocity section and by crowbarring the rails just behind the projectile as the projectile entered the demuzzling section.

Experimental Results

The projectile illustrated in Figure 2 has been fired three times, with the low velocity pressure increasing in each successive test. The first two tests and the railgun have been described previously.[2] In the third test, described here, the low-velocity operating pressure was increased to 0.7 GPa from 0.4 GPa. In all three tests, the projectile was successfully accelerated from rest and the guns were powered by explosive magnetic flux compression generators. In the present test, the operating pressure was not precisely known because of failure of the Rogowski loops. We estimate that the current rose to 0.8 MA at 90 μs, remained nominally constant until 400 μs and declined slightly to generator burnout at 500 μs. Preshot calculations had predicted that the current would rise from 0.8 MA to over a megampere at generator burnout. The disappointing generator performance may be attributable to mechanically inadequate mechanical connections from the generator to the gun. Tests of generators firing into dummy loads have shown that stout connections between the generator and the load can improve generator performance. Good measurements of projectile position were obtained with magnetic probes and in-flight flash X-ray (Table 1). The impact crater made by the 20-g projectile in a 15-mm thick steel plate is shown in Figure 3. Neither the polycarbonate disk nor the corundum disk are visible in the X-ray film (fig. 1). Apparently both disks shattered upon demuzzling. The fiberglass sleeve is not visible in the X-ray. It is not known if the sleeve cannot be resolved in the image or if the sleeve had been stripped at some time during firing.

Table 1. Projectile position measurements. The probes measure the position of armature roughly 1 cm behind the projectile, the X-ray measurements are taken from the back of the projectile.

	Position (m)	Time (μs)
Probe 1	0.078	226
Probe 2	0.180	322
Probe 3	0.281	396
Probe 4	0.383	450
Probe 5	0.485	490
X-ray 1	1.138	798
X-ray 2	1.580	998

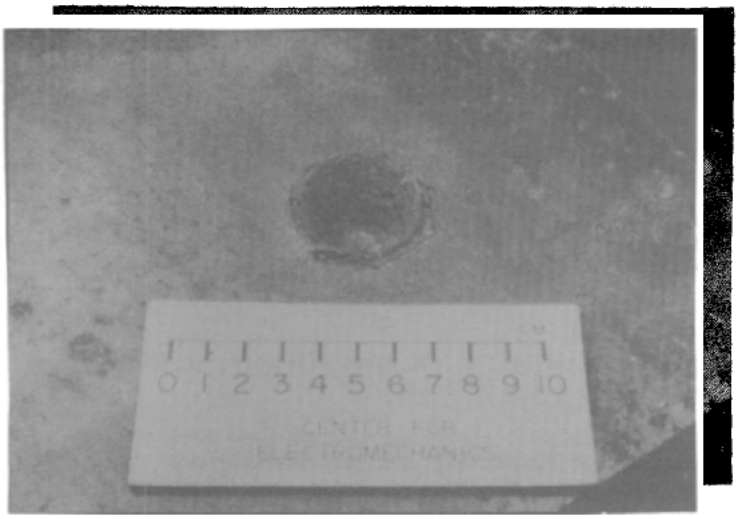

Figure 3. Impact crater of a 20-g titanium projectile in a 15-mm thick steel plate

The breech of the gun was sealed with a threaded polycarbonate plug (fig. 4). Post-shot inspection showed that the breech plug failed. The high pressure plasma produced by the fuse explosion was driven out the breech around the plug, tearing the insulation. This breech flash may be responsible for the failure of the Rogowski loops.

In the development of high pressure railguns, measurement of the deflection of the rails during firing provides useful information. One method of measuring rail deflection in the severe electromagnetic environment of the railgun is to drill sight holes looking at the top of the rail in the steel shell of the gun to pass X-rays. The deflection at the time of the X-ray is determined by comparing the resulting image with an image produced before firing. The measured deflection shown in Figure 5 is ~ 1 mm. Although the resolution of this method is low (~0.5 mm), this resolution is adequate for the large deflections encountered in high pressure railguns. Measurements can be made at several points along the gun with a single X-ray source by drilling a number of sight holes, appropriately slanted to converge at the X-ray source.

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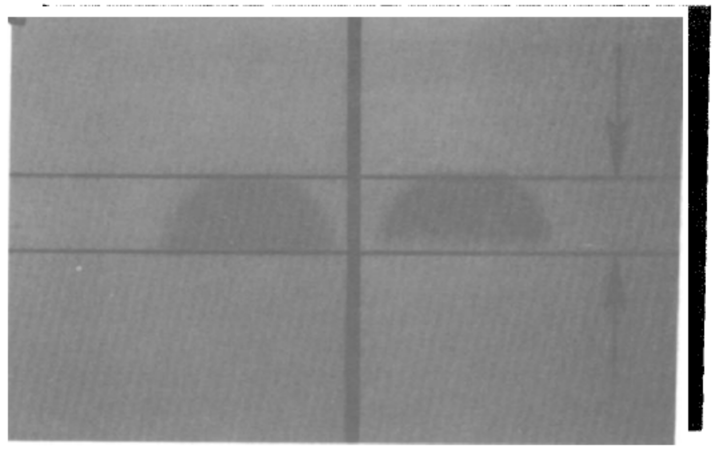

Figure 5. Rail deflection measurements using X-ray sight holes

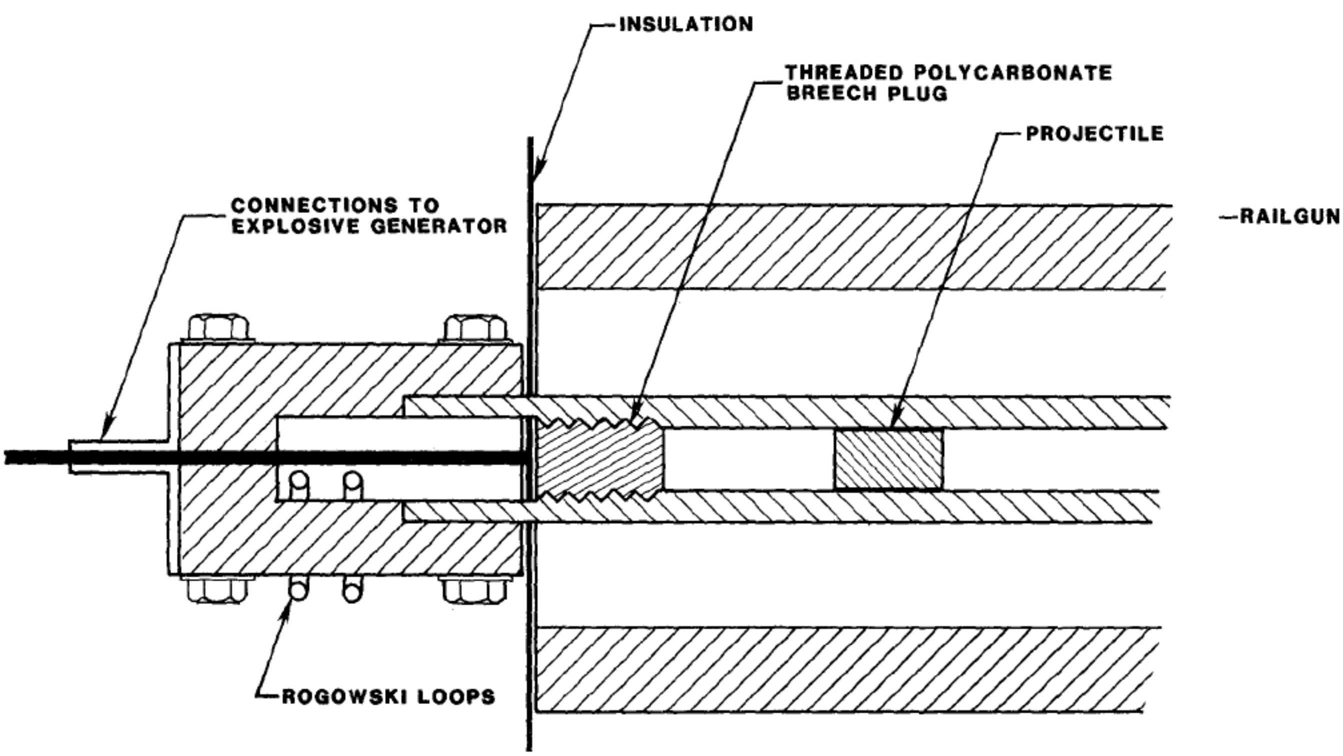

Figure 4. Design of breech plug and breech connections